Ideas on Designing a Reactor Neutrino Experiment to Make a Precision Measurement of θ_{13}

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March 15, 2003

Objective:

To design an experiment to search for a non-zero value of θ_{13} with a sensitivity of 0.01 at 90% confidence level, at $\Delta m^2 = 2.5\times10^{-3}$ (the value favored by Super-K) in three years of data taking.

Methodology

This analysis starts with the assumptions in the Kr2Det proposal:

- Two identical, 46 ton (fiducial) detectors at 115 and 1000 meters
- 55 events/day in far detector, 4200 near (Reactor $\Rightarrow$ ~2 GW_{therm})
- Reactor is on for 300 days in a year.
- Relative efficiency of near and far detectors know in 0.8%
- 600 mwe shielding $\Rightarrow$ Background of 0.1 events/ton/day

The actual background rate is assumed to be measured during reactor off days (65 per year).

Simple Counting Experiment

Look for disappearance in the ratio R, defined as

$$R = \frac{N_{far} L_{far}^2}{N_{near} L_{near}^2} \varepsilon$$

Where:

- The N's are the number of observed events
- The L's are the baselines and
- ε is the relative efficiency of the near and far detectors.

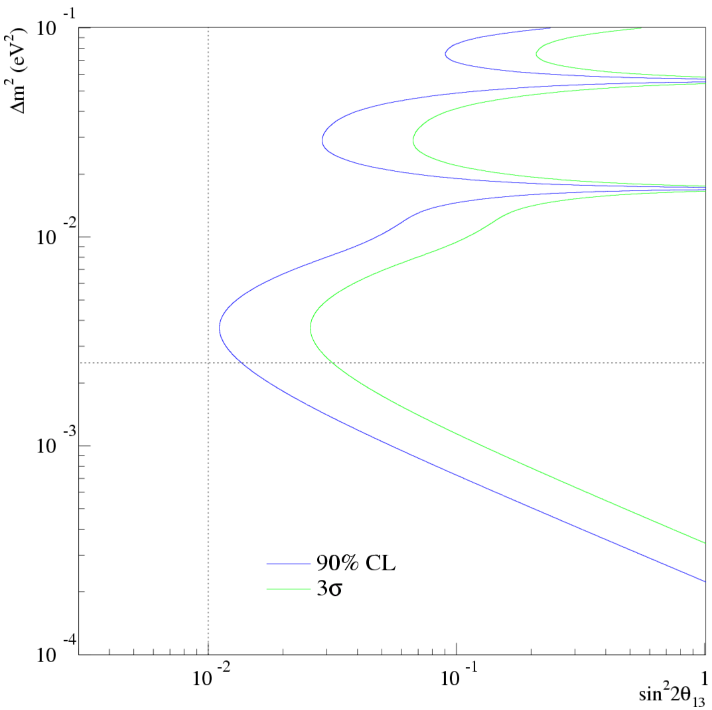
Disappearance is measured as a deviation of R from 1.

The sensitivity to disappearance is then σ_R.

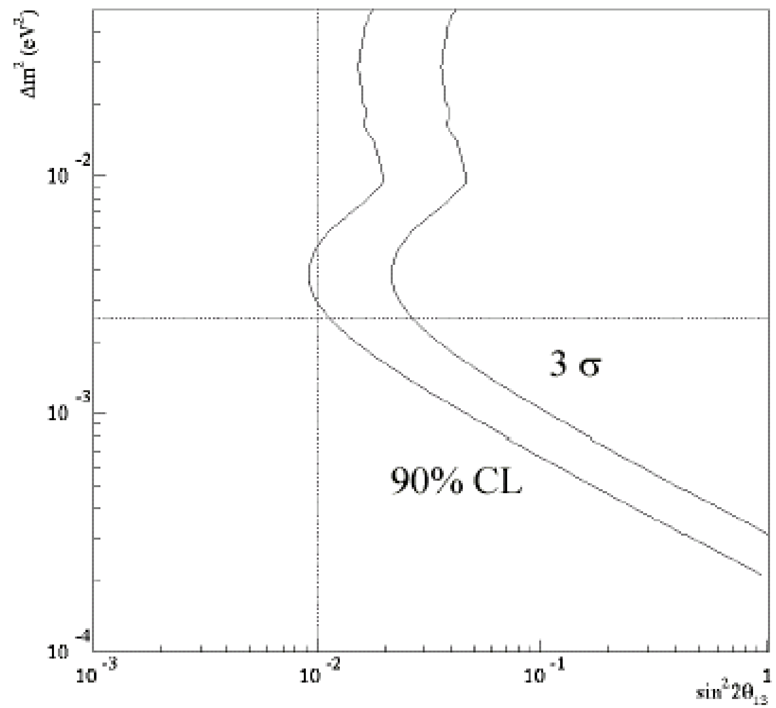
Counting vs. Shape

- Shape analysis improves the sensitivity.
- Counting experiment is sufficient to compare scenarios.

Wolf Creek Reactor (Kansas) After 3 Years



Counting Experiment



Shape Analysis

The Spreadsheet

den	0.85	g/cm^3	L near	115	m	coverage	0.2		bg	0.1	/ton/day
flux	2.00E+20	nu/s/GWth	L far	1000	m	diam_pmt	8	in	obs_bg	7.9935	
power_th	2		near flux	2.407E+11	/cm^2/s	area_pmt	0.03242928	m^2	tot_bg	101.507	
flux0	4.00E+20	nu/s	far flux	3.183E+09	/cm^2/s						
Hden	7.85E+22	H/cm^3	xsec*eff	5.59E-44	cm^2						
years	3										
uptime	3.38E+02										

This value is tuned to make the # of observed events come out right.

tons/unit fid	far units	active frac	bg sub	bg sub err	near event	near error	far tot/unit	far err/unit	far total	eff error	R error
46	1	1	4669	243.50298	4263948	2080.36	56390	346.91887	56390	0.008	0.0101
50	1	0.9	4567	228.48246	4171254	2056.22	55164	334.56724	55164	0.00219	0.00647
25	2	0.9	2283	161.5615	2085627	1453.96	27582	236.57371	55164	0.0031	0.00649
10	5	0.9	913	102.18046	834250	919.567	11032	149.61901	55164	0.0049	0.00654
5	10	0.9	456	72.252499	417125	650.232	5516	105.79425	55164	0.00692	0.00663
10	4	0.9	913	102.18046	834250	919.567	11032	149.61901	44131	0.0049	0.00729

far units = The number of identical detectors at the far location (n).

active frac = The fraction of time that each far unit spends at the far location (time spent at the near location is 1-active frac).

bg sub = The total number of background events subtracted from each unit.

near events = The number of signal events (after BG subtraction) seen by the near detector during the active fraction (N_n).

far events = The number of signal events seen by each far detector during the active fraction (N_f).

eff error = The error on the reletive efficiency (eff) of a far detector wrt the near detector as measured side-by-side.

R = far^2/near^2 * 1/n * sum(N_f*eff)/N_n

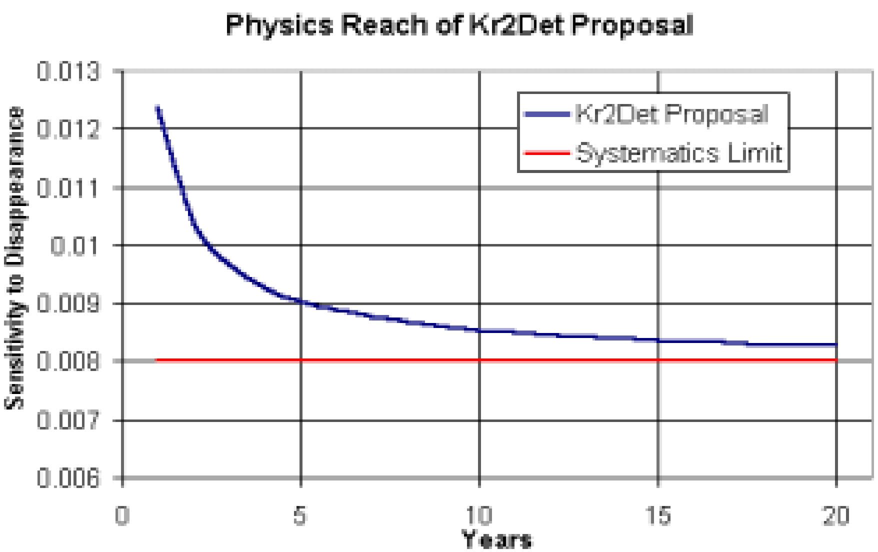
R error = The error on R.

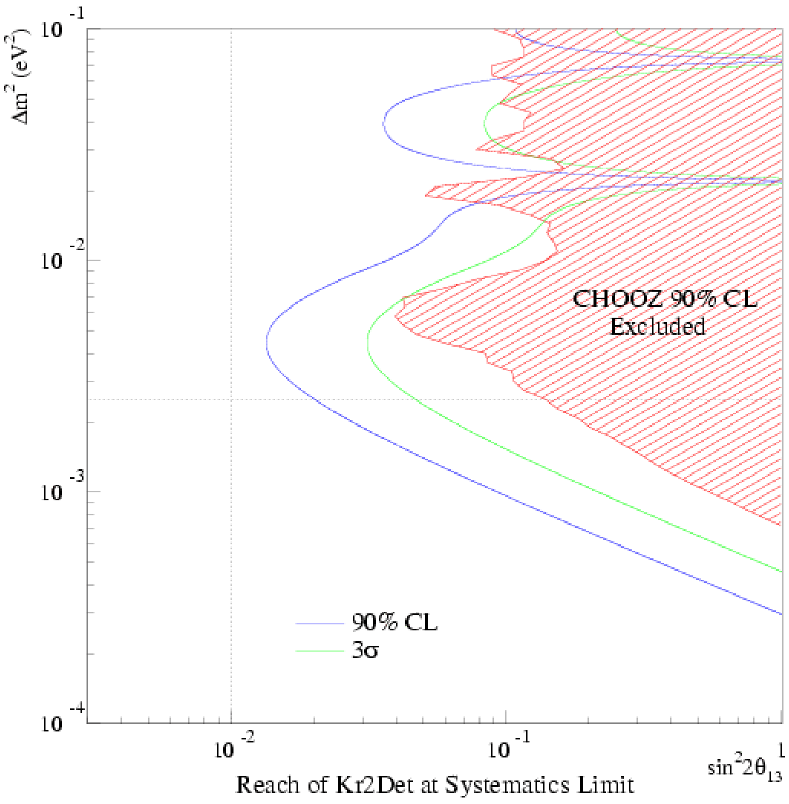
tons/unit fid	r fiducial	r total	far units	far fiducial	pmts/unit	pmts	tons/unit tot	near int/day	far int/day
46	2.34648	3.9964795	1	46	842	1684	340.903582	4200	55
50	2.412612	4.062612	1	50	876	1752	358.108679	4565	60
25	1.914891	3.5648914	2	50	640	1920	241.956738	2282	30
10	1.410904	3.0609041	5	50	439	2634	153.160915	913	12
5	1.119835	2.7698353	10	50	342	3762	113.490794	456	6
10	1.410904	3.0609041	4	40	439	2195	153.160915	913	12

This spreadsheet was used to model single reactor sites where the background could be directly measured using reactor off time.

Sensitivity of Kr2Det

Kr2Det is limited by the 0.8% error on the relative efficiency of their two detectors.





But we can do better with some modifications…

Modified Kr2Det Proposal

Movable far detector(s) that allow a direct measurement of the relative efficiency of near and far detectors in the near flux.

Possibly more than one (smaller) far detector to accommodate moving. One near detector identical to each far detector. Then

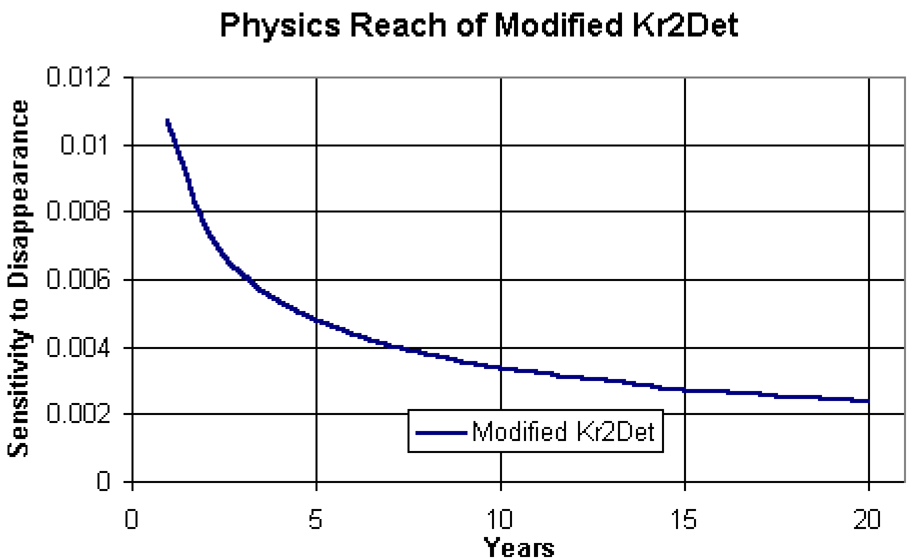
$$R = \frac{\sum_{i}^{n_{\mathrm{far}}} N_i L_{\mathrm{far}}^2 \varepsilon_i}{N_{\mathrm{near}} L_{\mathrm{near}}^2}$$

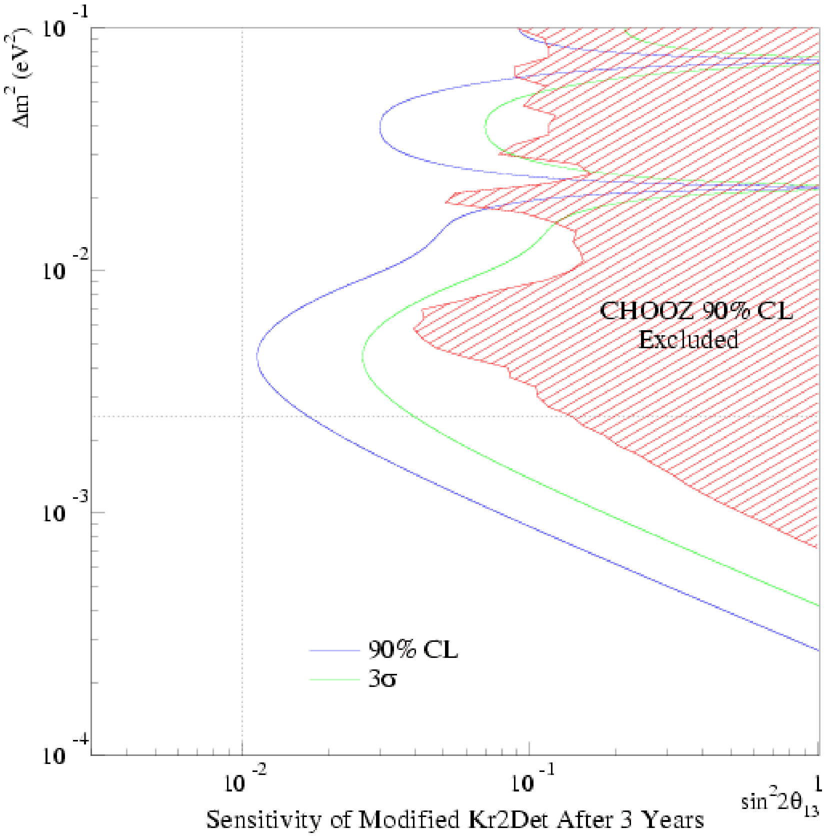
The limiting systematic of Kr2Det is now statistical and is tied to the measurement:

$$\varepsilon = \sqrt{2 N_{\mathrm{near}} f}$$

where f is the fraction of time near.

Sensitivity of Modified Kr2Det





With this modification you can get to a sensitivity of 0.01 at Δm^2 of 2.5×10^{-3} eV^2 by adding fiducial mass (132 tons) or time (8.5 years).

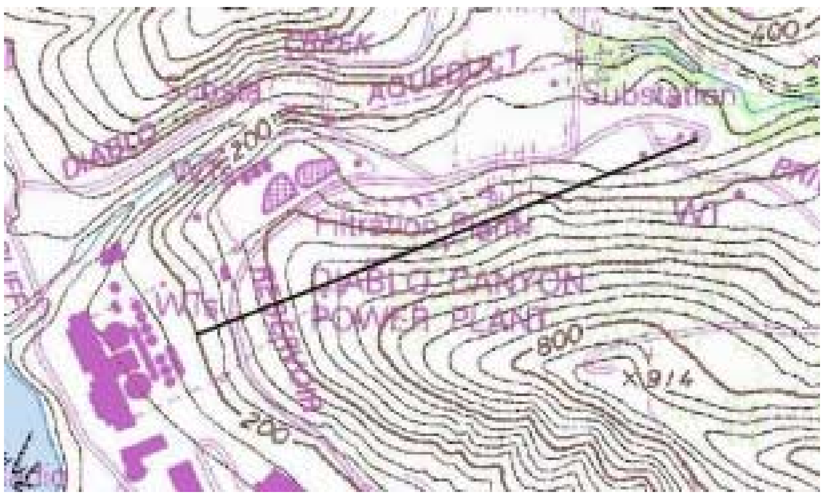
1000 meters is not the optimal baseline for sensitivity at Δm^2 of 2.5×10^{-3} eV^{2}.

Improve the Reach by Adding Reactor Power

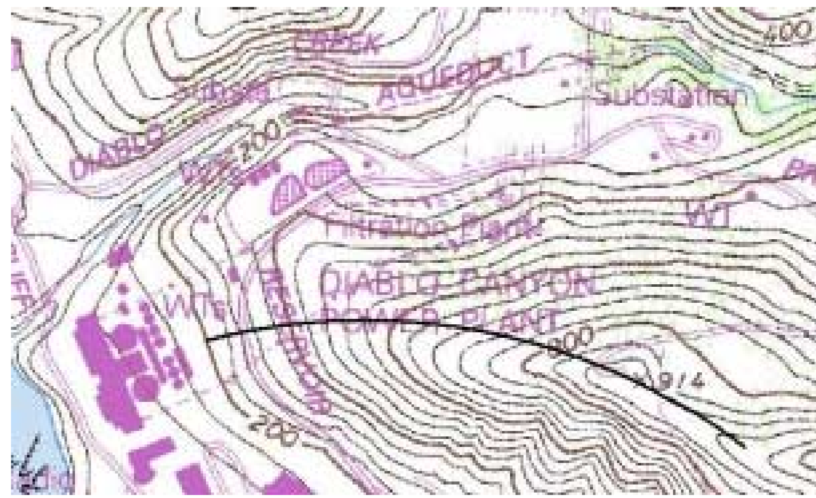
• The power of a modern reactor is typically $\geq$ 3 GW_{therm}.

• Up to two reactors can be used and still maintain the trivial flux normalization required for low systematic errors.

There are two ways to do this:



Equidistant from both reactors, does not require reactor flux data.



$(L_1/L_2)_{near}=(L_1/L_2)_{far}$, requires flux data to determine parameters in $\Delta m^2 - \sin^2 2\theta$ space.

We should expect a factor of 3 improvement over the Russian site.

Unfortunately…

At multiple reactor sites you don't get reactor off running.

So how do we measure the background?

- Use half power running (one reactor off) to extrapolate rate to zero power. (This method can be shown to be insufficient.)
- Use the "swap method" developed by Palo Verde.
- Use spatial (and temporal?) distributions between the positron and neutron capture events. (I will outline this idea later.)

How well must we know the background?

Background Sensitivity Study

We use a slightly modified spreadsheet that allows us to put in the expected number of background events and background error in %.

The experimental parameters used in this study are:

- 50 tons far fiducial mass
- 3 years
- Reactor power 6 GW_{therm}
- L_{near}=150 m and L_{far}=1200 m

At a depth of 300 mwe which, from CHOOZ translates to an expected background rate of 0.2 events/ton/day, we need to know the background rate to 3.5% or ± 345 out of 9855 events.

Perfect knowledge of the background improves sensitivity by 26%.

At 600 mwe (0.1 events/ton/day) we only need 7.5% or 4928 ± 369.

At 30 mwe (2 events/ton/day) you can't reach the desired sensitivity.

Background Definitions

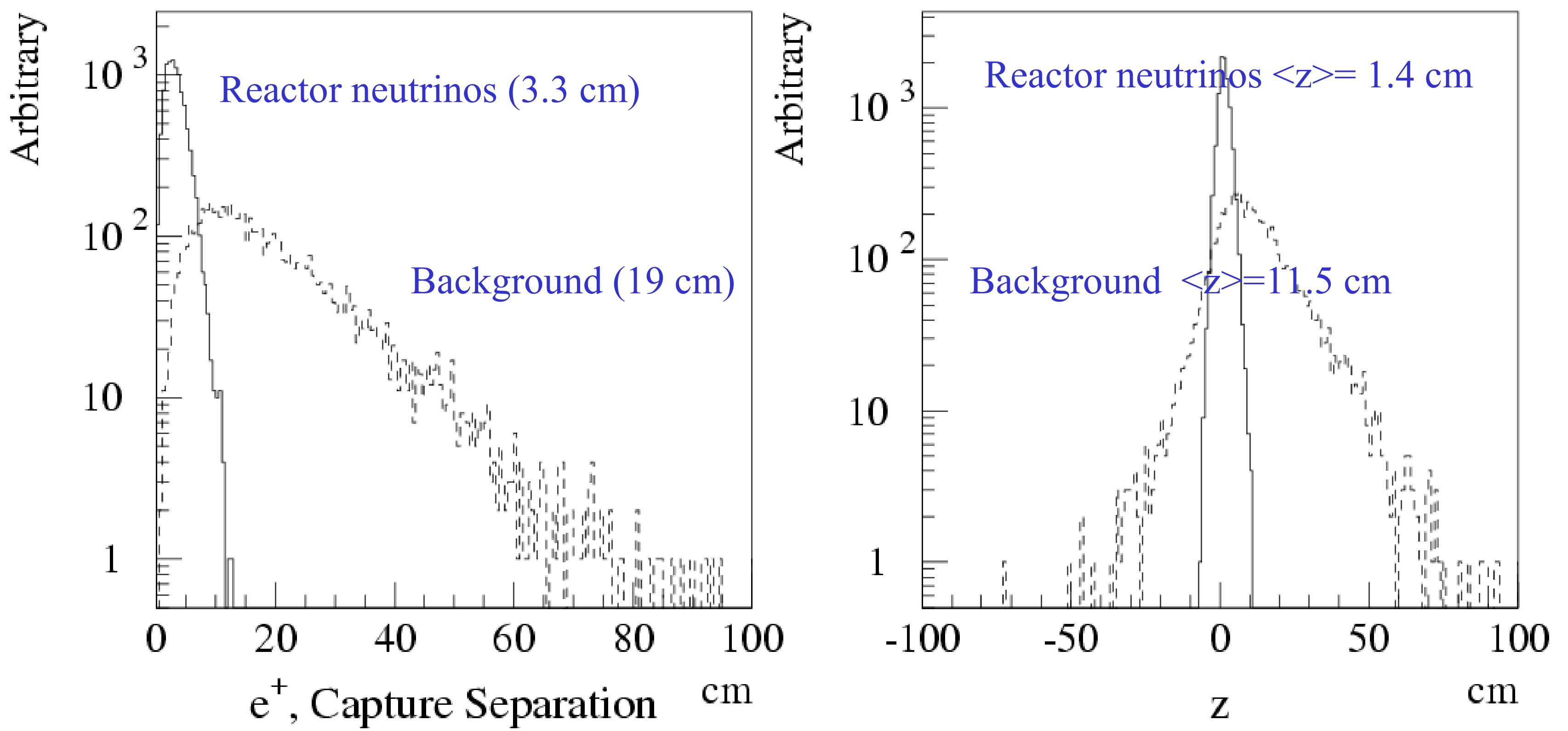
<u>Uncorrelated background</u> – the random coincidence of two unrelated events – can be estimated by triggering on neutron capture and positron events in the opposite time order.

<u>Correlated background</u> is caused by neutrons generated in the sourrounding material by cosmic ray muons. Either two neutrons are produced and are both eventually captured in the tank; or a single neutron strikes a proton that mimics the positron signal and is eventually captured in the tank.

We are primarily concerned with understanding the correlated backgrounds.

An Idea for Measuring Background to 3.5%

We expect a larger spatial separation of the two parts of the event for backgrounds.



There is also a tendency for neutrons to be captured forward, (i.e. in the exited the reaction) although I'm not yet sure how to use this.

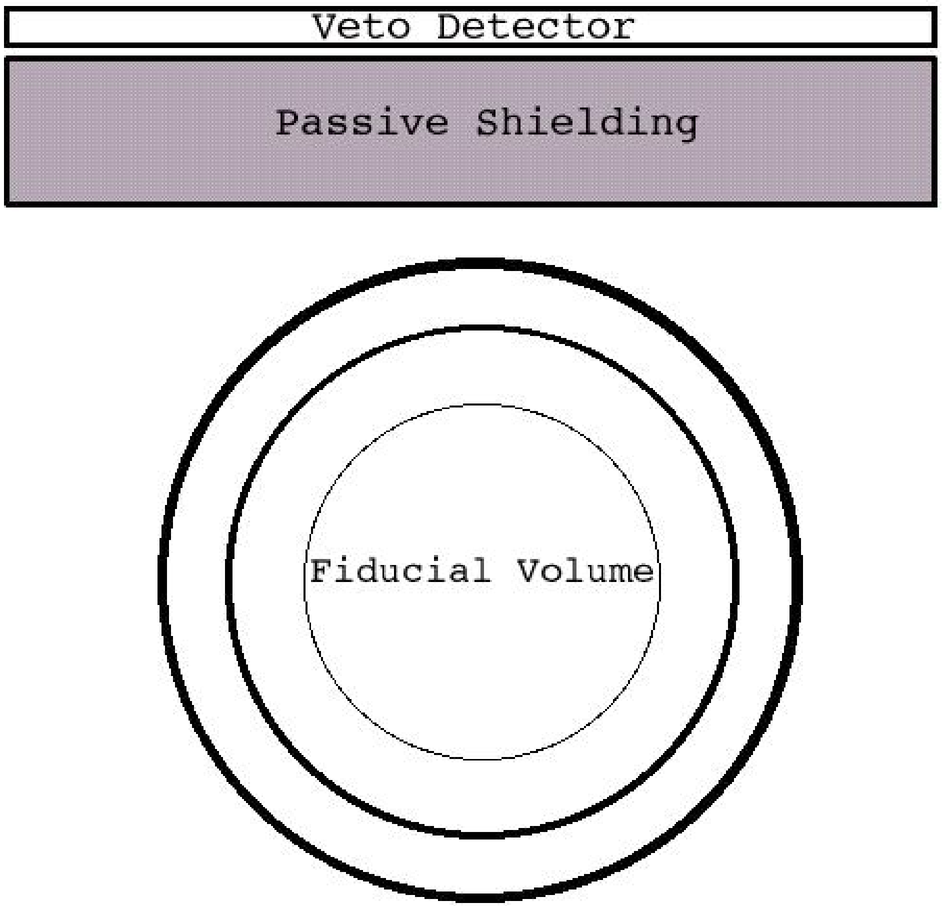
Directly Measure the Spatial Distributions

- Measure the signal spatial distribution with the near site running.

- Measure the background distribution by requiring events with a veto.

Veto detectors above (and beside?) the tank, separated from the tank by passive shielding would also reject most of the background.

The passive shielding would be thick enough to range out most muons produced outside the veto detector.



Caveats

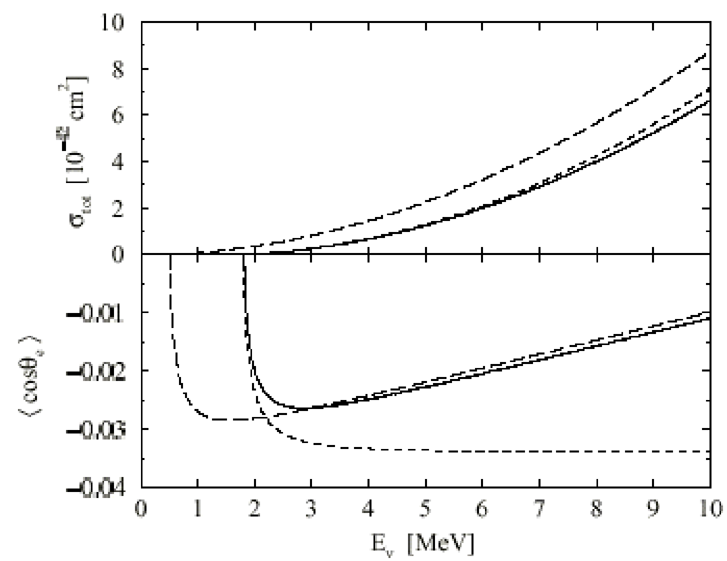
Things not in the simulated that might effect this analysis.

• Detector resolution.

• Photon mean free path from Gd capture, although there are typically more than one photons released in Gd-n capture.

• Positron recoil and path length.

• Proton recoil which will tend to be aligned with the neutron coming out of the collision.



Average positron recoil is backwards.
(Plot taken from Beacom and Vogel.)

Conclusions

- Kr2Det as proposed is not able to make a 1% measurement.
- A modified version of Kr2Det might be able to make the measurement, but it would either require more time or more fiducial mass.
- The measurement can be made faster at a more powerful reactor.
- Sites with two reactors can be used.
- At two reactor sites, new procedures for determining the correlated background would be required.
- One possibility involves using differences in spatial correlations for signal and background. More work is needed to demonstrate feasibility.